

# Globular cluster abundances and what they can tell us about galaxy formation

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**Abstract.** We review the properties of globular clusters (GCs) which make them useful for studying the Galactic halo, Galactic chemical evolution and the early stages of the formation of the Milky Way. We review the evidence that GCs have a chemical inventory similar to those of halo field stars. We discuss the abundance ratios for dSph galaxies and show that it is possible to have formed at least part of the Galactic-halo field stellar population by dissolving GCs and/or accreting dSph galaxies, but only if this occurred at an early stage in the formation of the Galaxy. We review the constraints on halo-formation timescales deduced from the low magnesium isotopic ratios in metal-poor halo field dwarfs, which indicate that asymptotic giant-branch (AGB) stars did not have time to contribute significantly, while M71 contains two populations, one without and also one with a substantial AGB contribution. We review the limited evidence for GCs with a second population showing additional contributions from Type II supernovae, currently confined to  $\omega$  Cen, M54 and M22, all of which may have been the nuclei or central regions of accreted galaxies. We check our own data for additional similar GCs and find preliminary indications that NGC 2419, a massive GC far in the outer Galactic halo, may also belong to this group.

**Keywords.** stars: abundances, Galaxy: formation, Galaxy: halo, globular clusters: general, galaxies: dwarf, Local Group

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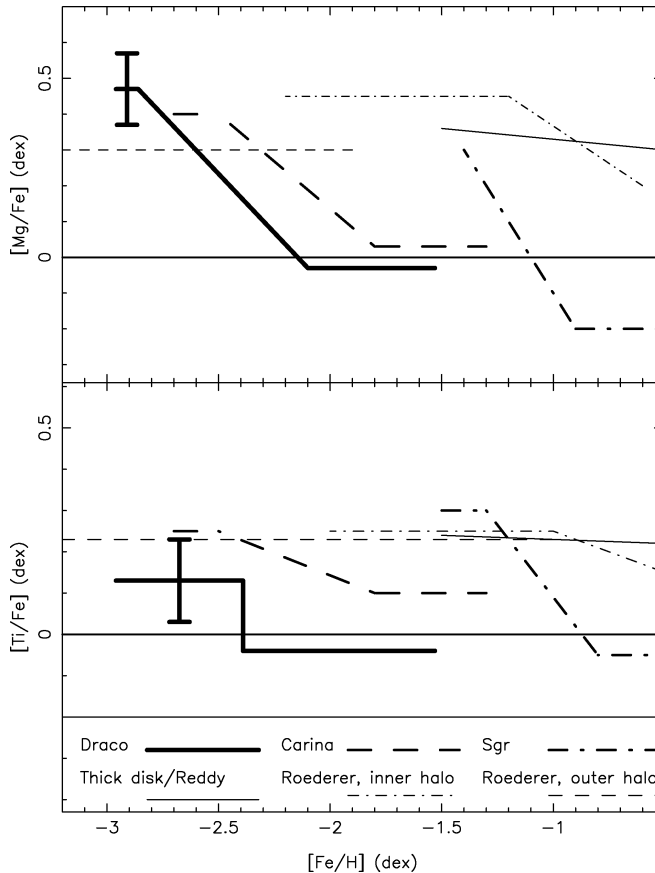
## 1. Introduction

Globular clusters (GCs) have unique attributes which make them laboratories for studying stellar evolution. Such stellar systems have well-determined distances and ages from their color–magnitude diagrams (CMDs), accompanied by detailed kinematic information based on large radial-velocity surveys. They show no evidence for the presence of dark matter, having mass-to-light ratios expected for old stellar systems. Their chemical inventories can be studied at high spectral resolution and with large samples of stars in a given cluster. Proper motions are available in some cases, leading to orbit determinations. Tidal tails are seen in a few cases, constraining mass models for the halo. Since Galactic GCs are old, with typical ages of  $\sim 12$  Gyr, and are, at least to first order, formed of stars with identical chemical compositions, they can provide unique insights into the formation of the Milky Way galaxy.

Some of the key issues involving GCs that are of great current interest are to what extent there are multiple populations in GCs and to what extent they are chemically homogenous. Also, whether the Milky Way halo could have been made at least in part by dissolving GCs and accreting dSph satellite galaxies, whether the GCs and the halo have the same metallicity distribution function (MDF), whether they have the same chemical inventory and what we can learn from them about early supernovae (SNe), star formation and formation of the Galactic halo.

## 2. Globular cluster abundance ratios versus halo field stars and dSph satellites

It has been clear for several years now that the abundance ratios  $[X/Fe]$  for Galactic halo field stars show trends with  $[Fe/H]$ . Broadly speaking, the ratios increase to a super-solar level as  $[Fe/H]$  decreases for the  $\alpha$  elements, while they decline for Cr I and Mn I, with minimal scatter about the mean relations, implying that the halo is well mixed with many SNe contributing to the chemical inventory of each star. A major theme of work over the past few years has been to extend these relations to ever more metal-poor halo field stars and explore the subtle differences that may exist in chemical inventory between stars in the inner and outer parts of the Galactic halo, subjects not part of the current discussion. However, over the metallicity range characteristic of the Galactic GCs, it is now well established that the GCs, ignoring those associated with the dissolving Sgr dSph galaxy, follow the trends established by the halo field stars, see e.g. the review of Gratton *et al.* (2004). Detailed chemical-evolution models for the Galaxy, such as those of Matteucci (2009) or Kobayashi *et al.* (2006), can reproduce most of these trends. One long-standing issue, resolved in Schoerck *et al.* (2009) using the MDF for



**Figure 1.**  $[Mg/Fe]$  (*top*) and  $[Ti/Fe]$  (*bottom*) in three dSph satellites (Draco: Cohen & Huang 2010; Sgr: Monaco *et al.* 2005; Sbordone *et al.* 2007; and Carina: Koch *et al.* 2008) as a function of  $[Fe/H]$  compared to the trends for Galactic field halo stars from Roederer (2008) and thick-disk stars from Reddy *et al.* (2006) as well as for Galactic GCs. See figure 21 of Cohen & Huang (2009) for details.

Galactic halo field stars inferred from the Hamburg/ESO Survey with corrections for selection efficiency is that it is probably not statistically significant that there is no GC with  $[\text{Fe}/\text{H}] < -2.4$  dex given the very low fraction of extremely metal-poor stars in the halo.

Another issue is that of the abundance ratios and MDFs for the satellite dSph galaxies of the Milky Way compared to the Milky Way halo. Helmi *et al.* (2006) summarized the position of the very large DART survey at the *VLT*, claiming that the dSph galaxies lacked the expected fraction of extremely metal-poor (EMP) stars, which are found in the Galactic halo, and that this and other related evidence from the behavior of abundance ratios of the  $\alpha$  elements precluded the possibility of making the Galactic halo in whole or part from dissolved dSph galaxies. This controversial paper has been refuted, and now even the authors admit that it is flawed. It is clear from a large number of recent studies, including that of Cohen & Huang (2009) for the classical dSph galaxy Draco and of Kirby *et al.* (2008) for the recently discovered ultrafaint satellite galaxies, that the local dSph galaxies have an appropriate (low) fraction of EMP stars, and that at the lowest Fe metallicities,  $[\alpha/\text{Fe}]$  in such low-luminosity satellite galaxies is quite close to the values for similar-metallicity stars in the Galactic halo. At later times, the star-formation history of the dSph galaxies diverged strongly from that of the halo and strong differences in chemical inventory and abundance ratios arose between them. Thus, the bulk of the accretion must have been early, as is expected from cold dark-matter hierarchical galaxy-formation models and simulations.

### 3. Elements known to vary within GCs and why

The anticorrelation between O and Na is ubiquitous among GCs. The range is very large, sometimes a factor of 10 in abundance of each, and is seen at all luminosities of the member stars. There is also an anticorrelation between Mg and Al, sometimes with a very large range in Al (a rather rare element, so burning only a small amount of Mg into Al will produce a big change in the Al abundance). GC stars show large star-to-star variations of C and N, almost always with C and N anticorrelated, see e.g. Cohen *et al.* (2005). None of this is seen among samples of halo field stars. All of this is tied to horizontal-branch characteristics, Galactic orbits, almost certainly to He abundances, and is evidence for at least two generations of star formation in GCs, as is discussed in a long series of papers by E. Carretta and collaborators, the most recent of which is Carretta *et al.* (2010).

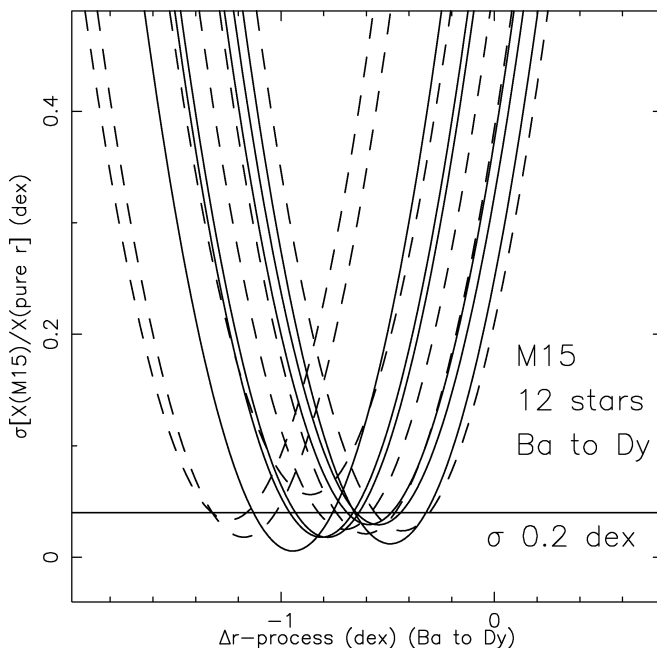
Star-to-star variations of elements between Ca and Ni within GCs is discussed in Section 5. Moving on to the heavy neutron-capture elements beyond the Fe peak, M15 is the one GC known to show a star-to-star variation among them, first detected by Sneden *et al.* (1997) (see also Otsuki *et al.* 2006). I (unpublished) have verified that the variation in abundance among the heavy neutron-capture elements within M15 is about a factor of five, and the production mechanism for these heavy elements is the r-process, rather than the s-process. Results for a sample of 12 red giant-branch (RGB) stars in M15 are shown in Figure 2. The low minima in  $y$  indicate that the heavy elements in M15 originate in the r-process. The range in  $\Delta r$  (the  $x$  coordinate of the figure) of the minima for the curve for each M15 star indicates the range in the fractional r-process contribution to the chemical inventory of the M15 stars. These are very rare elements,  $\epsilon(\text{Eu})/\epsilon(\text{Fe}) \sim 10^{-11}$  in M15, so small star-to-star variations within a very metal-poor GC should not be surprising.

#### 4. Constraints from isotopic abundances

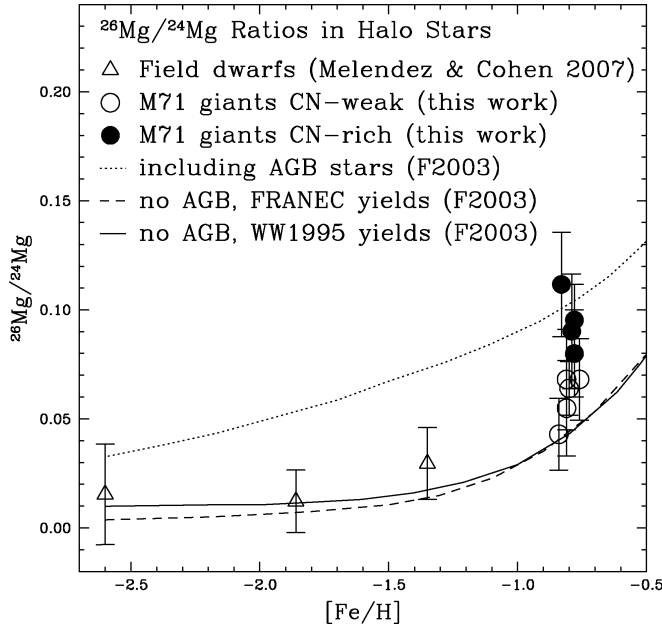
Isotopic abundance ratios can convey still more detailed information than atomic abundance ratios as production of a particular isotope requires specific nuclear reactions. The ratios among the three stable isotopes of Mg, all of which can be formed in massive stars (Woosley & Weaver 1995) are of particular interest as they provide a rough chronometer.  $^{24}\text{Mg}$ , the most common isotope, is formed as a primary isotope from H, while  $^{25,26}\text{Mg}$  are formed as secondary isotopes. The heaviest Mg isotopes are also produced in intermediate-mass AGB stars (Karakas & Lattanzio 2003), so the isotopic ratios  $^{25,26}\text{Mg}/^{24}\text{Mg}$  increase with the onset of AGB stars. Therefore, Mg isotopic ratios in halo stars can be used to constrain the rise of the AGB stars in our Galaxy and—if the AGB contribution is not present—the minimum timescale for halo formation.

Measurement of the Mg isotopic ratios requires detection of weak contributions from the rarer heavier Mg isotopes in the wings of much stronger  $^{24}\text{MgH}$  lines, hence exquisite spectra of very high spectral resolution ( $\sim 100\,000$ ) and very high signal-to-noise ratio, as well as careful attention to details of the line list used for the spectral synthesis and to the analysis procedure.

This idea is applied in two papers written with my former postdoc, Jorge Meléndez, who did most of the work, Meléndez & Cohen (2007, 2009). We see no sign of an AGB contribution among our sample of metal-poor Galactic halo dwarfs. In the GC M71, at  $[\text{Fe}/\text{H}] -0.7$  dex, we see two populations, as shown in Figure 3. The first has weak CN, normal O, Na, Mg and Al, and a low ratio of  $^{26}\text{Mg}/\text{Mg}$  ( $\sim 4\%$ ), consistent with models of Galactic chemical evolution with no contribution from AGB stars. The second population has enhanced Na and Al, accompanied by lower O and by higher



**Figure 2.** Deviations from a scaled r-process are shown for 12 stars in the GC M15. The  $y$  value for each star is the rms of the difference between  $[X/\text{Fe}]$  for the M15 star and that assuming a pure r-process distribution scaled by  $[\text{Fe}/\text{H}]$  for M15 with a fixed offset,  $\Delta r$ , over the elements between Ba and Dy for which abundances have been derived in the star, typically six elements.



**Figure 3.** Our  $^{26}\text{Mg}/^{24}\text{Mg}$  ratios in both field dwarfs (triangles; Meléndez & Cohen 2007) and M71 giants (Meléndez & Cohen 2009) as a function of  $[\text{Fe}/\text{H}]$ . Chemical-evolution models by Fenner *et al.* (2003) including (dotted line) and excluding (solid and dashed lines) AGB stars are shown. (Figure from Meléndez & Cohen 2009.)

$^{26}\text{Mg}/\text{Mg}$  ( $\sim 8\%$ ), consistent with models which incorporate ejecta from AGB stars via normal stellar winds. We therefore infer that the timescale for formation of the first generation of stars we see today in this GC must be sufficiently short to avoid a contribution from AGB stars, i.e., less than  $\sim 0.3$  Gyr.

## 5. Variation of Type II supernova contributions

Spectroscopic evidence for multiple populations in Galactic GCs has been known for a long time based on studies of the O–Na anticorrelation and on spreads in the CNO abundances among stars within a particular GC as reviewed by C. Charbonnel at this meeting. These require at least two generations of GC stars, with the second polluted by ejecta from either AGB stars or massive rapidly rotating stars.

The existence of multiple generations of stars within GCs has very recently been detected using photometry as well. The sample of GCs with CMDs based on ACS images taken with *HST* has grown rapidly, most recently through the ACS Survey of Galactic Globular Clusters (an *HST* Treasury project) (Sarajedini *et al.* 2007). This extremely accurate photometry has enabled detection of subtle features in the GC CMDs that were previously lost in the noise, including multiple main sequences, a double subgiant branch in NGC 1851 (Milone *et al.* 2008) and other such phenomena.

They are usually explained by small differences in age, He content (which, although difficult to detect directly, must occur in association with the O/Na anticorrelation and the CNO variations) or metal content. When invoking the latter, one must be careful to distinguish between variations among those elements such as CNO, which can be produced by ejecta from intermediate- or low-mass AGB stars, and variations in the heavier elements such as Ca or Fe, which are only produced in SNe. Presumably at such

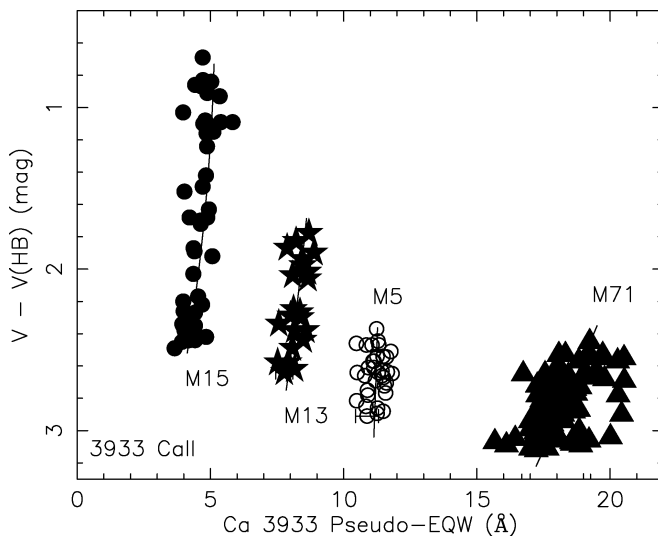
early times, Type II SNe (SNII) are the culprit rather than Type Ia SNe. Great care is required to distinguish among the various possibilities.

The issue of a second generation of SNII contributions is of particular interest, since it is hard to understand how a low-mass GC with low binding energy could retain energetic SNII ejecta, unless the GC we observe today were a remnant of an initially much more massive stellar system. So, the question at hand is whether there are any other such cases, in addition to  $\omega$  Cen (known for more than 30 years), to have a wide intrinsic range in  $[\text{Ca}/\text{H}]$ ,  $[\text{Fe}/\text{H}]$ , etc., extending over a range of  $\sim 1.3$  dex with multiple peaks (Norris *et al.* 1996). The GC M54 also shows this, but it is believed to be part of the central region of the Sgr dSph galaxy, currently being accreted by the Milky Way. Very recently M22, under suspicion for many years, was confirmed to have such by Marino *et al.* (2010), who suggest a range in  $[\text{Fe}/\text{H}]$  of perhaps  $\sim 0.15$  dex.

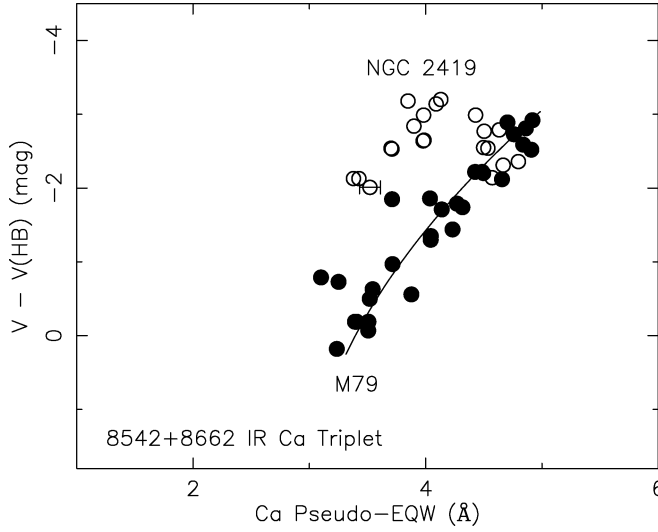
Are there more such cases? Is this the tip of the iceberg? Do other GCs all have more modest variations in  $[\text{Fe}/\text{H}]$ ? A literature search for recent detailed abundance analyses of samples of GC stars, almost always luminous RGB stars, indicates that  $\sigma[\text{Fe}/\text{H}]$  is quite small in these clusters compared to the obvious cases described above; they show dispersions in Fe abundance of less than 0.05 dex (10%), and sometimes as low as 5%. A careful check of a large sample of GCs, particularly of the most massive objects, is desirable as some of the most massive Galactic GCs are not well studied.

As a preliminary step towards this goal, I have checked the spectra from *Keck*/LRIS slitmasks I took from 1998 to 2003 for a study of CH, CN and NH bands with P. Stetson and M. Briley. These cover the H and K lines of Ca II. I measured the strength of absorption in the 3933 Å line. Results are shown for four GCs in Figure 4. I have also located a substantial number of *Keck*/Deimos slitmasks of Galactic GCs which cover the 8500 Å Ca-triplet region, two of which were analyzed prior to this IAU Symposium, shown in Figure 5. These spectra were taken for other purposes and are not optimized for the present goal, but still yield upper limits to  $\sigma[\text{Fe}/\text{H}] \sim 0.03$  dex in the best cases.

Ignoring M71, which has substantial field-star contamination due to its low Galactic latitude, the most interesting result is that for NGC 2419, a massive GC far out in the halo at a distance of 84 kpc. The data in hand appear to show a substantial range of



**Figure 4.** Equivalent width of the 3933 Å line of Ca for samples in four GCs as a function of luminosity below the horizontal branch.



**Figure 5.** Sum of the equivalent width of the 8542 and the 8662 Å lines from the Ca triplet for samples of upper-RGB stars in M79 and NGC 2419, as a function of luminosity.

[Ca/H], which is probably not due to field-star contamination. Efforts are now underway both to establish the limiting accuracy that can be reached by such techniques and to verify this interesting result, as—if valid—NGC 2419 must represent the remnant of a former Milky Way satellite.

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